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Punch Response of Gels at Different Loading Rates

by Mark Foster, Paul Moy, Joseph Lenhart, Randy Mrozek,
and Tusit Weerasooriya

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<tr><td colspan="6">14. ABSTRACT
A novel punch test was developed to screen possible candidates for biological tissue surrogates. Materials included 10% and 20% ballistic gelatin, the commercially marketed Perma-Gel, triblock copolymer gels, and silicone-based polymer gels. These gelatin materials are being investigated for uses in biomedical applications, injury characterization, and body armor verification experiments. The limitations of ballistic gelatins have deemed them as unusable for many of these applications because of the gelatins' lack of toughness, short shelf and functional lifetimes, and temperature sensitivity. To determine which materials offer the most promise from the multitude of synthetic gelatin solutions, the punch test was developed as a screening method. Results are then compared to a previous study on tensile fracture of gel materials for test validation.</td></tr>
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1. Introduction

Ballistic gelatin has a long-proven record for the testing and evaluation of armaments. This protein-based material is useful to compare the relative effectiveness of projectiles in different situations because it has a similar density as muscle tissue. Each armament system is typically evaluated by sizing the temporary and permanent wound cavity formed when the gelatin is impacted with a ballistic projectile. A direct correlation between cavity size and actual injury is difficult to obtain using this method. Projectiles will yaw or tumble after a certain depth of penetration, which forms the temporary cavity related to tissue disruption (*1*). The irregular shape of these cavities complicates a direct comparison of cavity size. Schyma and Madea (*2*) have developed a technique using paint to help define the void size in these tests, but a direct measurement is still lacking. Ballistic gelatin has been shown to be sensitive to temperature and have a limited shelf and functional lifetime, which can be counted in hours (*3*). This requires ballistic gelatin to undergo a calibration process each time it is used; the material is checked to a standard penetration depth of a certain size and velocity projectile. Because of these factors, ballistic gel is not well suited to a quantitative testing method required to verify a wide spectrum of injury mechanisms.

In order for a body armor system to be effective, the armor must absorb or redistribute the energy of the incident projectile. Typically this occurs through fast deformation of the armor surrounding the body. This deformation of the armor will impart stress waves and high-rate displacements to the underlying tissue, which can be fatal in extreme cases (*4*, *5*). Such loading of the body is referred to as behind-armor blunt trauma (BABT). Researchers test current body armor systems for BABT by using a back surface deformation measurement technique that involves a block of clay set behind the armor surface. After the projectile impact event, the permanent cavity imprinted into the clay block is measured for depth, and this measurement is related to the overall armor effectiveness. The clay material must be calibrated at a constant temperature and reworked if it fails calibration (*4*, *6*). While similar in density, neither clay nor gelatin simulates the tissue structure of the human body accurately. Danelson et al. (*7*) developed a urethane lung instrumented with pressure transducers to create a risk assessment for pulmonary contusion, a common injury associated with BABT. However, the hardness of the urethane was much higher than that of true lung tissue because such a soft tissue would be unable to support itself. Merkle et al. (*8*) have created a human surrogate torso model (HSTM) with embedded sensors that enable individual pressure readings amongst different surrogate organs. This is a great step toward a standard target to assess BABT injury criteria, but the HSTM requires materials that mimic the load response of human tissue.

Recent work on gelatins has shown promise in robotics, sensors, and microfluidics (*9*). Hydrogels (water-based gelatins) have been investigated in biomedical uses, such as tissue scaffolds (*10*, *11*), drug carriers (*12*), or impurity removal (*13*). Despite this widespread attention, hydrogels suffer from similar limitations as ballistic gelatin, with strong temperature dependence, limited lifetime, and low toughness characteristics. These issues can be alleviated, however, if the solvent is built from low-volatility organic molecules (*14*).

Gelatins are either protein or polymer based. The synthetic polymer gels typically comprise a solvent in a cross-linked polymer network. Many formulations of a synthetic gelatin are possible, each with different mechanical properties from varying levels of molecular entanglement and cross-link density. The use of such a large array of material characteristics and testing conditions prohibits direct characterization of even a small fraction of the possibilities. A better method to begin testing these materials was determined to be a screening process to relate the biaxial penetration response of a selection of synthetic gelatins to that of ballistic gelatin at a variety of loading rates. An appropriate screening process would quickly determine which gels could have behaviors similar to true biological tissues.

The results from this basic screening test would be compared to prior results from tensile tear tests to validate the method (*15*). This prior work consisted of a notched dog-bone specimen that was pulled in tension while a digital image correlation (DIC) system recorded strain values as a preformed crack propagated through the specimen. The technique involves using digital images of a high-contrast, random pattern of speckles and a sophisticated optimization program to measure full-field deformation. Figure 1 shows an example of the information that can be obtained from this technique.

While an effective method, the DIC technique does introduce additional variables. All the variables of a camera system, such as depth of field, shutter speed, and camera resolution, must be balanced with the test parameters. In addition, the black and white pattern must be able to adhere to gelatins of different polymer composition while stretching to strains well over 100%. These factors led to the development of a simple punch test to be used as a screening process.

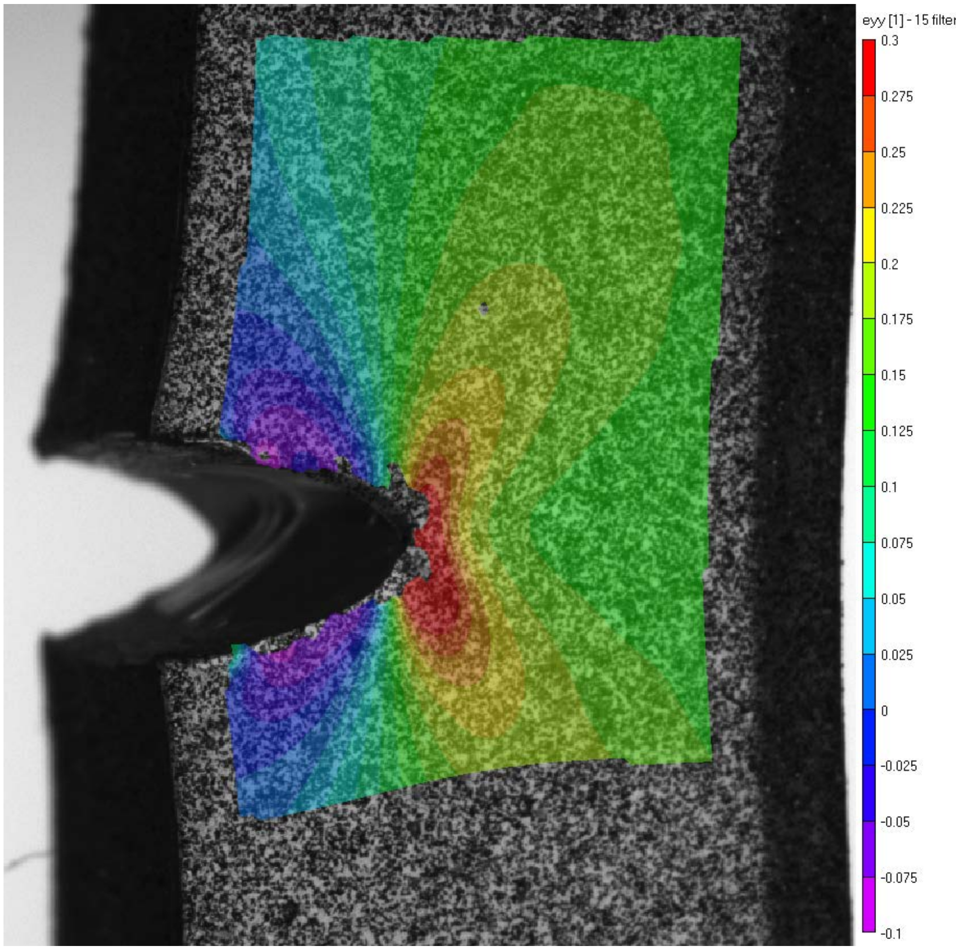


Figure 1. DIC strain measurement on gelatin crack propagation experiment (*15*).

2. Experiment

Various gelatin materials were subjected to loading by a hemispherical penetrator tip moving at a constant velocity. These materials included synthetic polymer gels, ballistic gels, and Perma-Gel, a commercially available ballistic gel replacement. One group of synthetic polymer gels was made from different concentrations of poly(styrene-*b*-ethylene-co-butylene-*b*-styrene) (SEBS) G1652 as-received from Kraton Polymers (Houston, TX, USA) and mineral oil as-received from Aldrich Chemical (Milwaukee, WI, USA). These three gels were mixed and cast into sheets with concentrations of 70%, 80%, and 90% mineral oil to SEBS polymer.

The other group of synthetic gelatins was polydimethylsiloxane (PDMS)-based polymers with a nonreactive PDMS solvent. The solvent molecular weight was varied to closely determine the corresponding effect on the material properties; specifically, m-PDMS weights of 28,000 g/mol (T28); 62,700 g/mol (T63); and 128,000 g/mol (T128) solvents were investigated.

Ballistic gelatin was made from Bloom 250 Type A ordnance gelatin mix as-received from GELITA USA (Sioux City, IA). Each batch was mixed in water according to manufacturer directions, poured into a sheet, refrigerated, and tested the following day. Ballistic gels of either 10% or 20% by mass gelatin are those typically used for bullet penetration tests, and both are accounted for here (*16*).

Perma-Gel is a transparent material designed to have similar properties to ballistic gelatin but without its inherent lifetime and temperature limitations. The material was used as-delivered and was cut from a large base block, melted, cast into sheets, and allowed to cool before testing.

Each 4-mm-thick specimen was glued (cyanoacrylate) to one side of a 7/16-in washer with a outer diameter of 1 3/8 in and tested to full failure with a 1/4-in hemispherical indenter that was coaxially aligned with the center of the washer. All specimens were checked for voids or foreign material prior to gluing. Specimens were then placed on an elevated table fixture that incorporated a 45° mirror to view the rear surface of the sample. This table fixture was fixed to the base of an Instron 8871 servohydraulic load frame that controlled and directly measured the displacement and measured the resultant corresponding force required to indent the gel specimens. The overall machine setup can be seen in figure 2. Bluehill software recorded the displacement and force data from the load frame.

Lubrication was used to minimize friction between the gel and the penetrator. For ballistics gels, a regular olive oil was used, while silicone oil was used for the Perma-Gel and SEBS synthetic gels, and mineral oil was used for the PDMS-based gelatins. Each was selected to ensure compatibility with the base material, and similar viscosity was sought so as to minimize relative friction effects between different groups of gelatins.

Traditional strain measurement methods posed problems when applied to gelatin materials. Strain gages were unable to be adhered to the gelatin surface using traditional methods and could not fully characterize the three-dimensional deformation that occurred during penetration. Extensometers also pose problems with these materials because their sharp contact points create localized loads and cause premature failure. Therefore, data acquisition was restricted to load and displacement as provided by the load frame.

Three different displacement rates were addressed: 12.7, 127, and 1270 mm/min. These gave input into a wide range of material characteristics while remaining within the capabilities of the load frame.

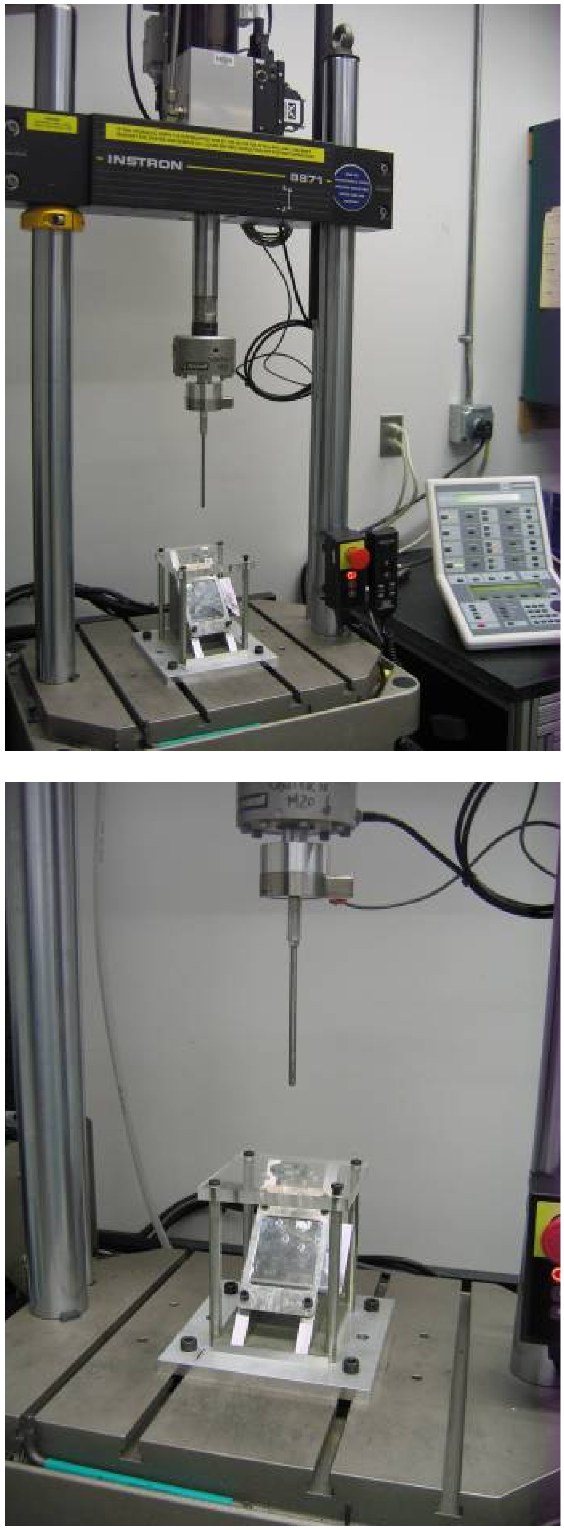
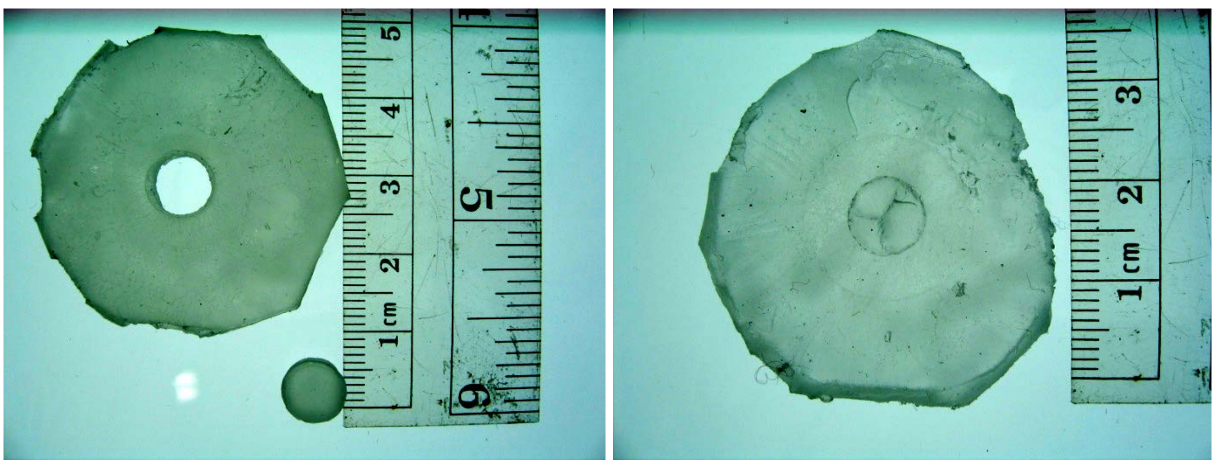


Figure 2. Test fixture and load frame.

3. Results and Discussion

Friction between the indenter and the gelatin dominated much of the preliminary testing. When oil was omitted, specimens would exhibit a mode III shearing failure instead of the desired biaxial failure. This was indicated by the presence of a separated plug and corresponding hole remaining after the gelatin was tested. While the addition of lubricant did minimize frictional effects, many of the PDMS gelatins still showed the undesired shearing failure mode, with a small plug remaining after the test was complete. The two failure modes are depicted in figure 3. This may be an artifact of the material polymer structure, and it was seen that different diameter plugs were produced from experiments at different extension rates. Average load and displacement data obtained for all materials at each extension rate are shown in figures 4–9 for the various rates of displacement. These plots include error bars to indicate variability in the load for the samples of each type of material.



(a) (b)

Figure 3. Failure types of gelatin specimens: (a) shear "plug" type and (b) biaxial "splitting" type.

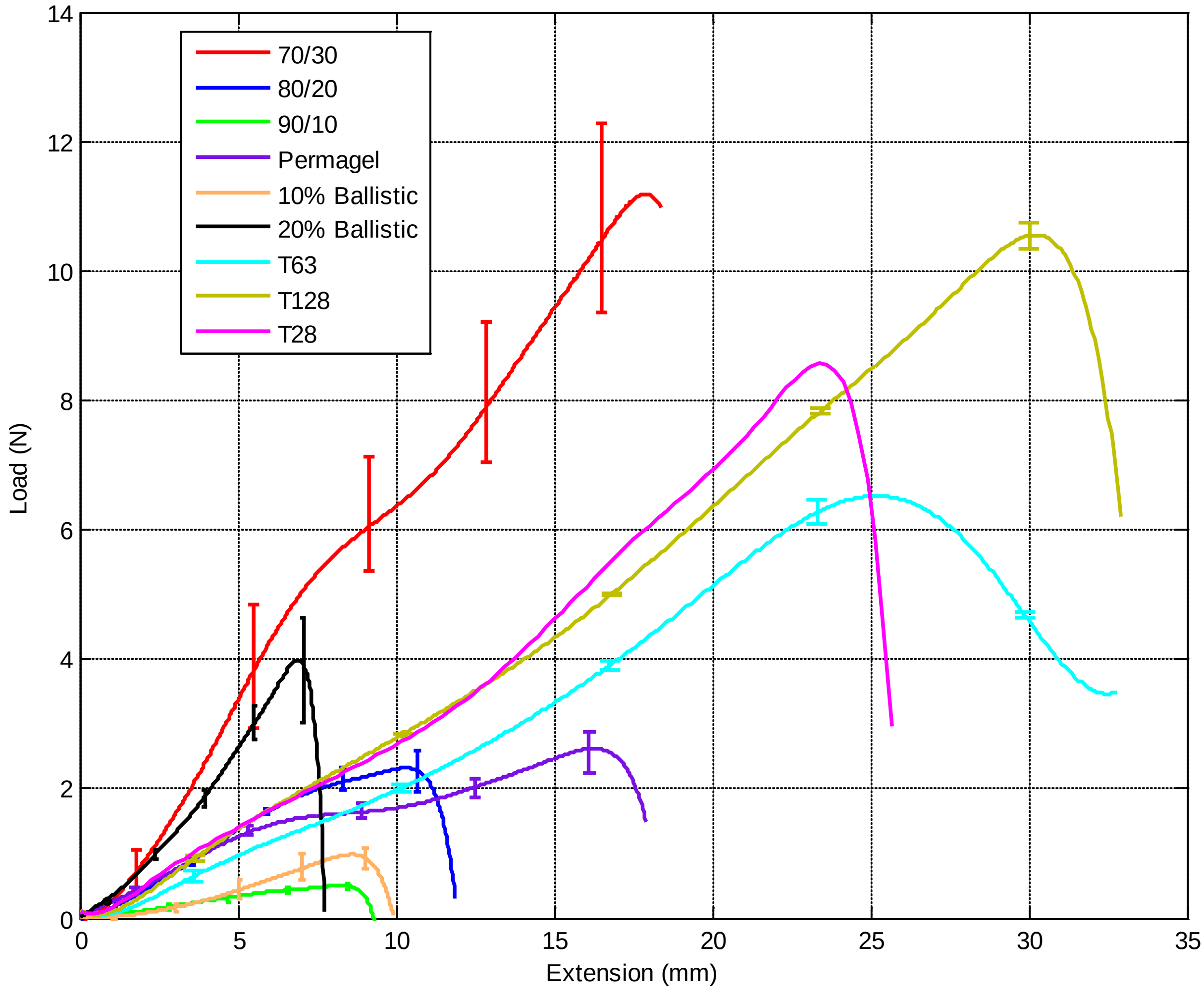


Figure 4. Load-extension response of all materials at 12.7 mm/s.

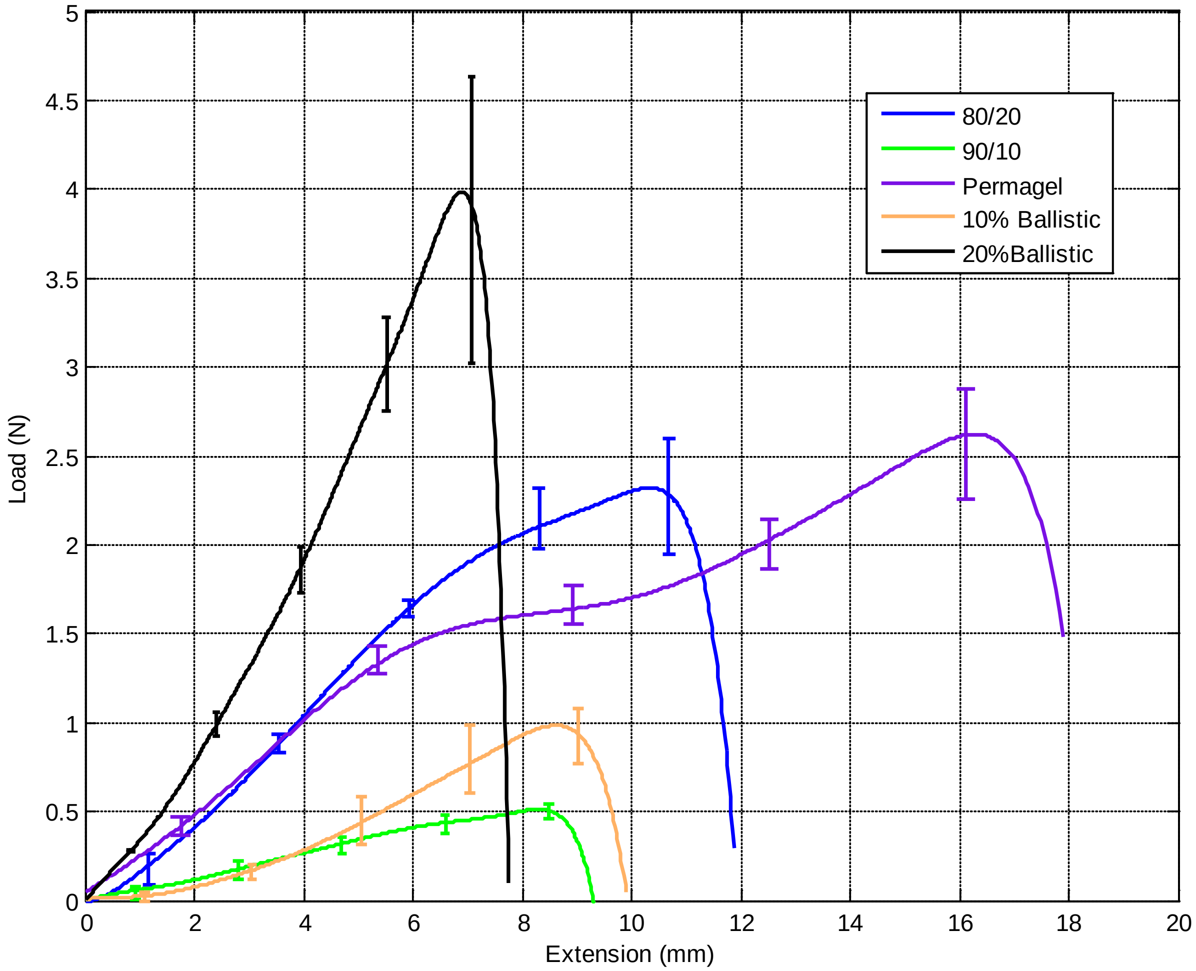


Figure 5. Load-extension response of softer materials at 12.7 mm/s.

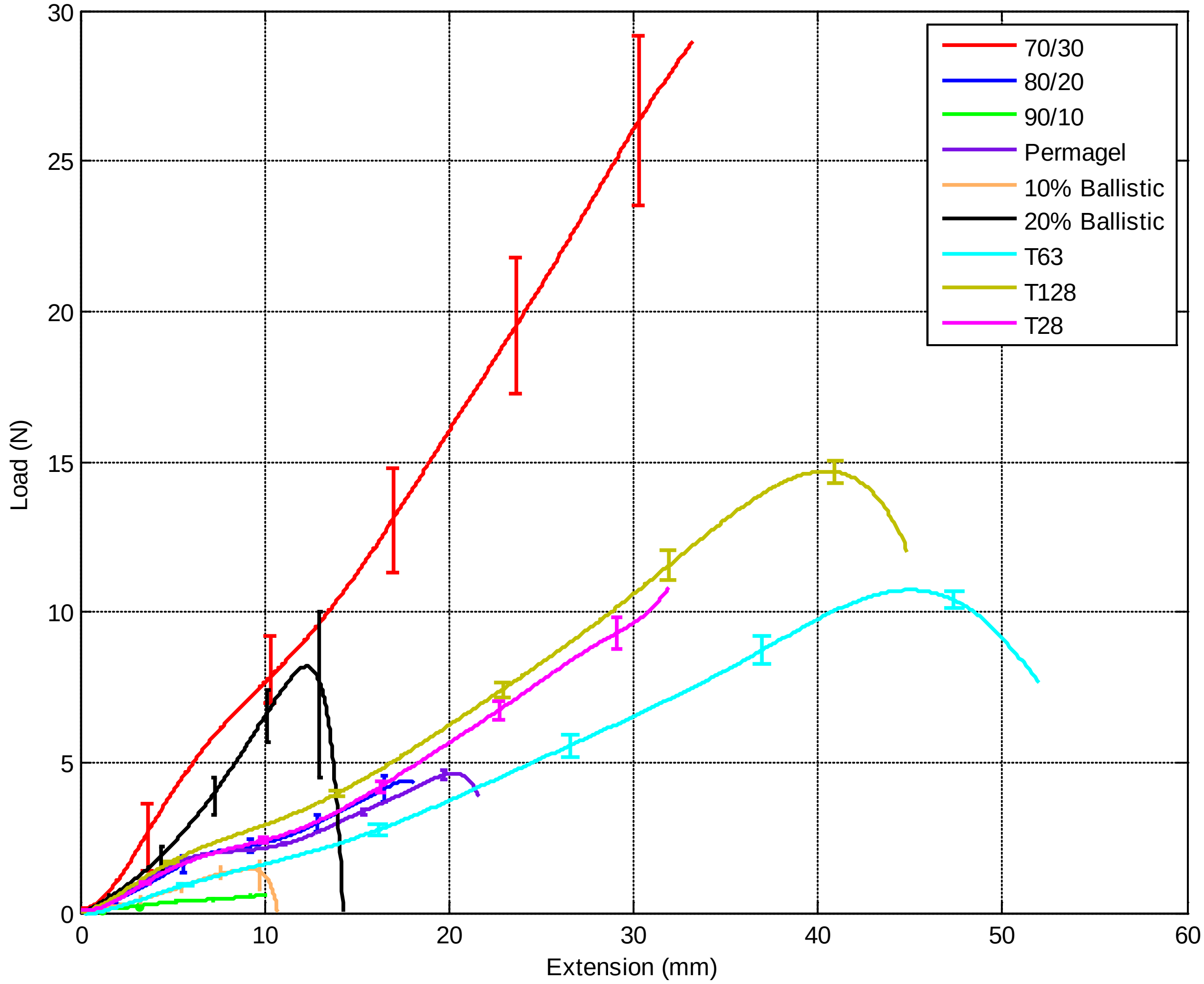


Figure 6. Load-extension response of all materials at 127 mm/s.

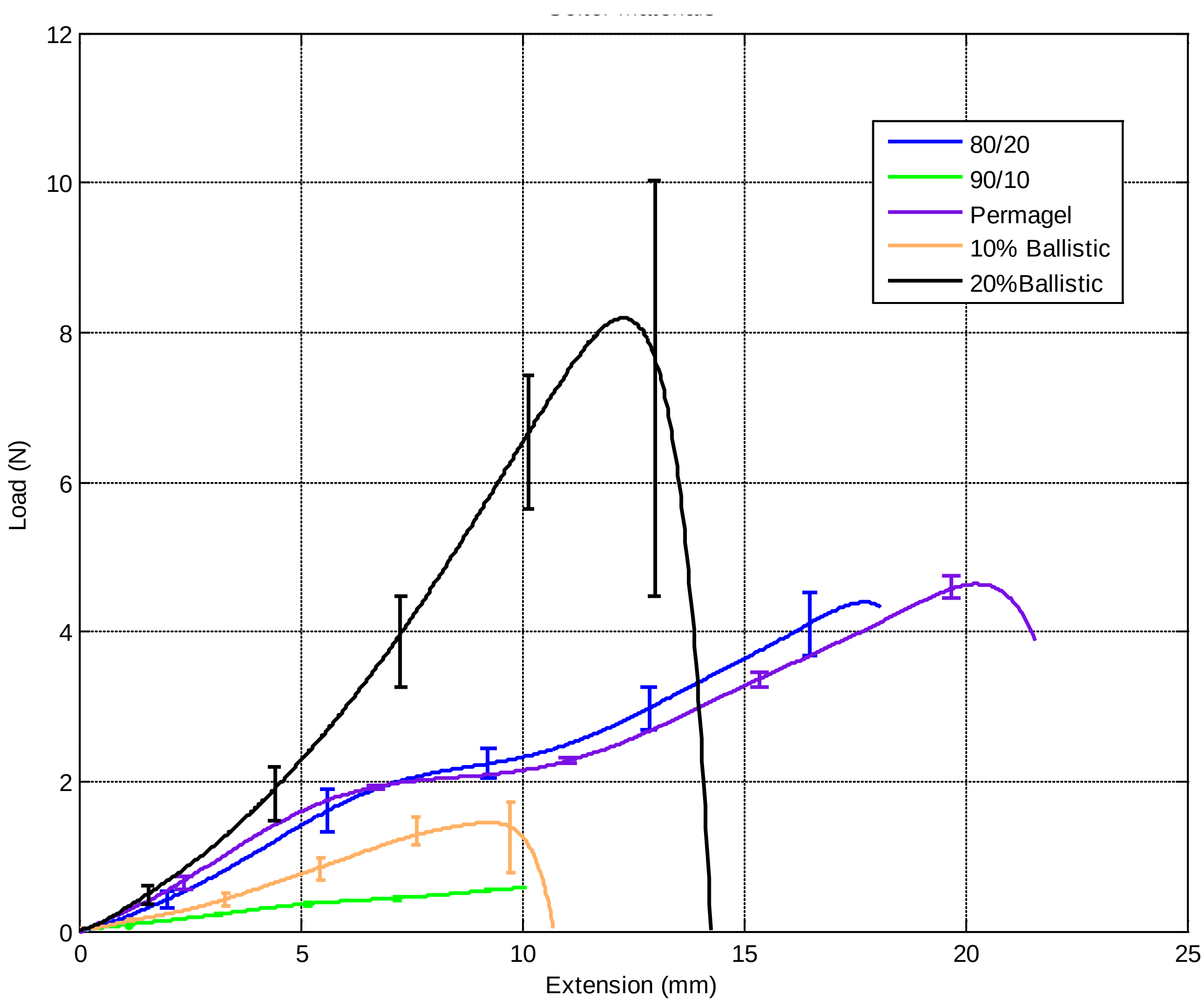


Figure 7. Load-extension response of softer materials at 127 mm/s.

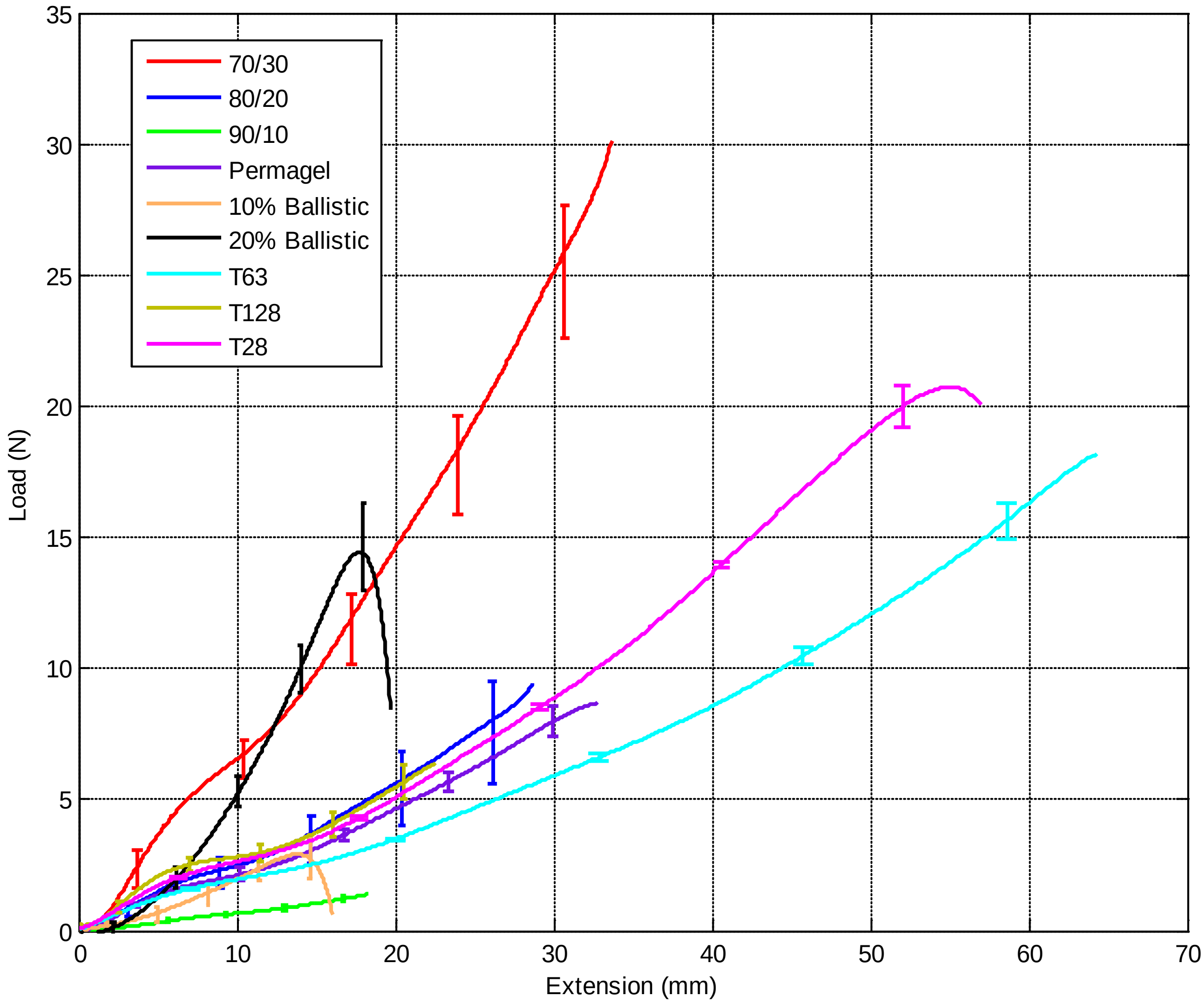


Figure 8. Load-extension response of all materials at 1270 mm/s, inset is figure 9 range.

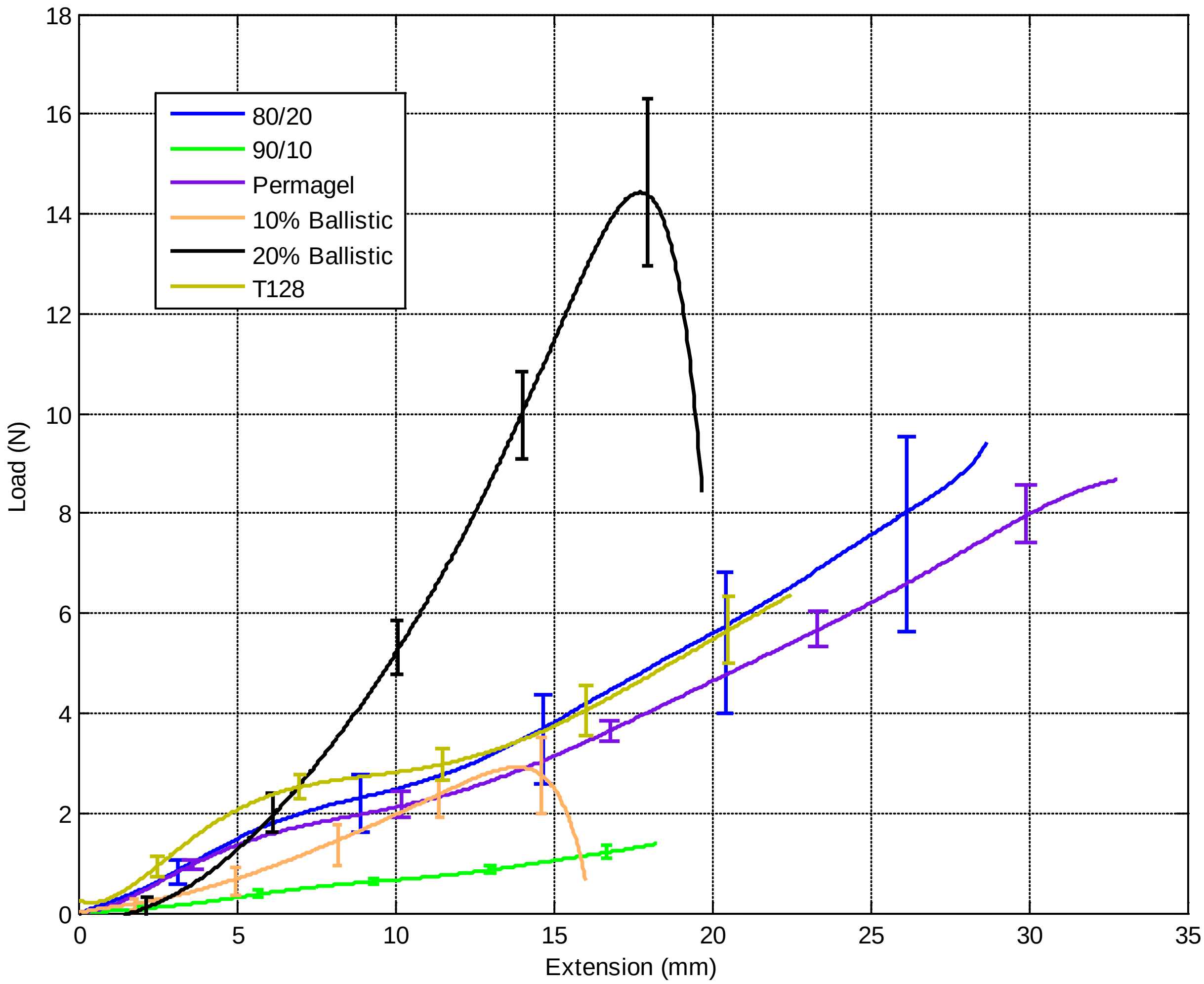


Figure 9. Load-extension response of softer materials at 1270 mm/s.

Many materials had a similar initial response, such as the close agreement between 80/20 and Perma-Gel for all three rates. However, the ballistic gels do not exhibit the flat relaxation portion of the load-displacement curve that the other materials expressed. This response is exhibited as a softening portion in the load-extension curve and is shown in both the Perma-Gel at 8- to 10-mm extension at the 12.7-mm/min rate, and also the T128 at 9- to 12-mm extension at the 1270-mm/min extension rate.

Rate dependent parameters were mixed. For example, the ballistic gelatins showed increases in load and extension to failure with an increase in displacement rate, while the SEBS gels gave similar responses at both 127 and 1270 mm/s. Interestingly, the T128 formulation of PDMS-based gels had a reduced strength and extension at the 1270-mm/s rate. This behavior was unlike the other two PDMS formulations, T28 and T63.

The ballistic gels also show lower overall extensions than the other synthetic materials, most notably in comparison with the PDMS-based gelatins, which had a much larger extension to failure. This is likely due to a difference in overall material toughness, which is largely dependent on the interaction of cross-linked polymer content and solvent molecular weight in the synthetics (*6*). It would then be easy to assume that the differences in response between the ballistic and the other synthetic gelatins are a direct result of their individual strengthening mechanisms. While the ballistic gelatins are known to exhibit a hyperelastic behavior (*17*), which is apparent here in the initial concave-upward shape of their load-extension curve, the synthetics all share a more linear response but with a certain reduced stiffness around 30% to 40% the extension to failure. This small low stiffness region may be derived from the microstructure of the synthetics, with perhaps different portions of the cross-linked polymer contributing to different loading regimes as the material is stretched to full failure.

Punch test data were then compared to existing results on Perma-Gel and the two concentrations of ballistic gels. The energy required to punch the gel was compared to the previous energy data from the fracture testing. This comparison is shown in figures 10–12.

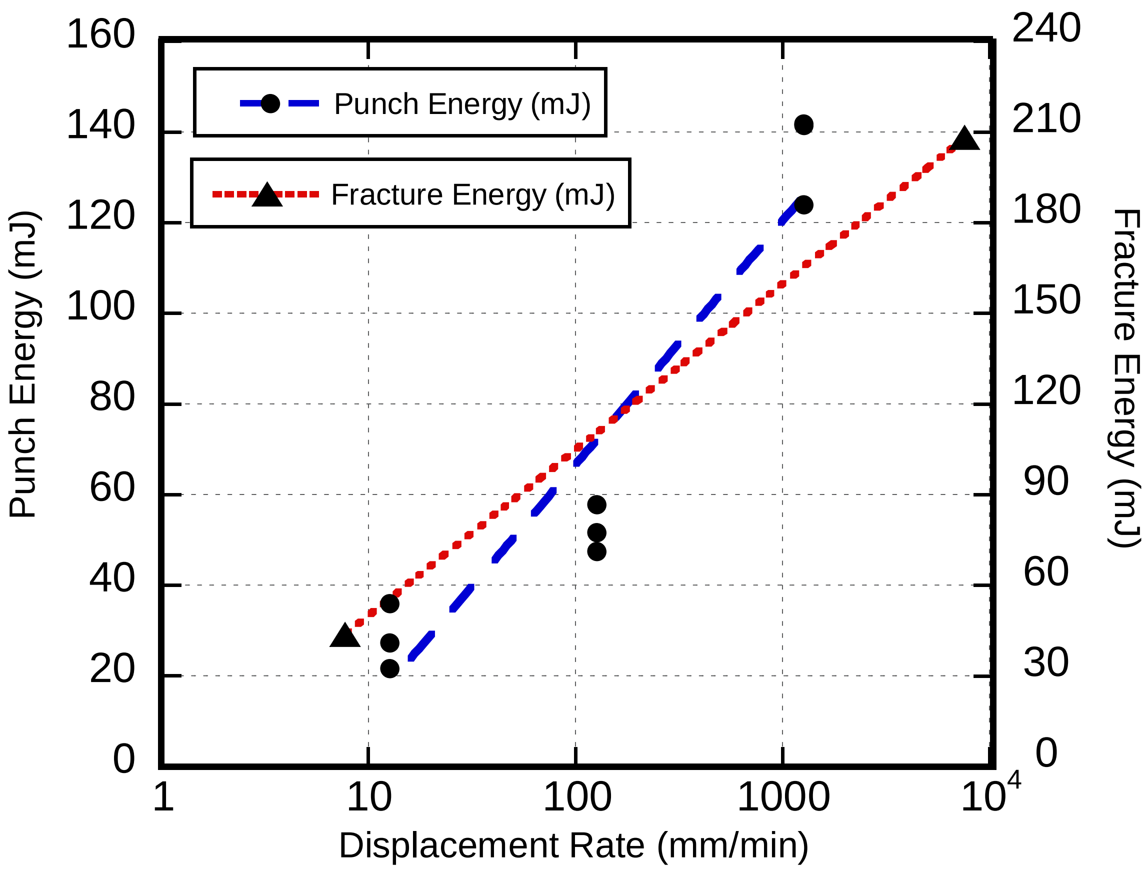


Figure 10. Relationship between punch energy and fracture energy for Perma-Gel.

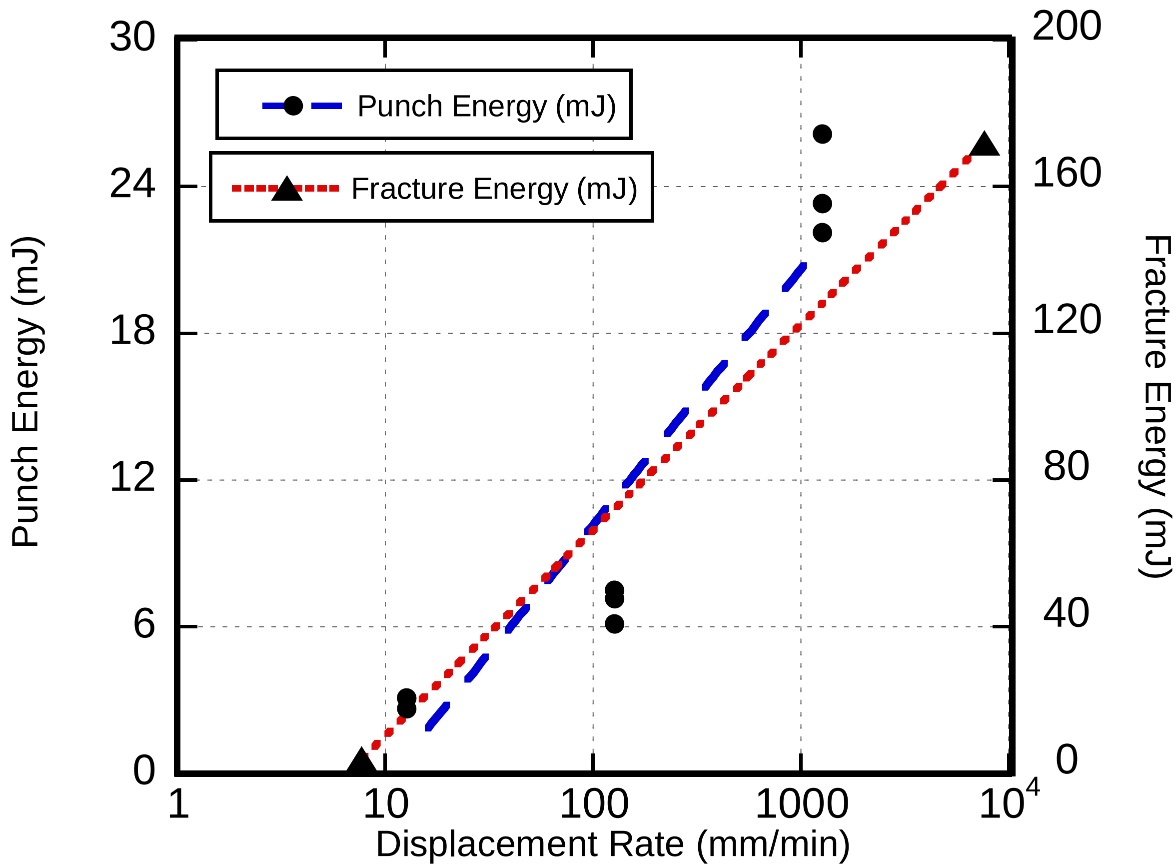


Figure 11. Relationship between punch energy and fracture energy for 10% ballistic gelatin.

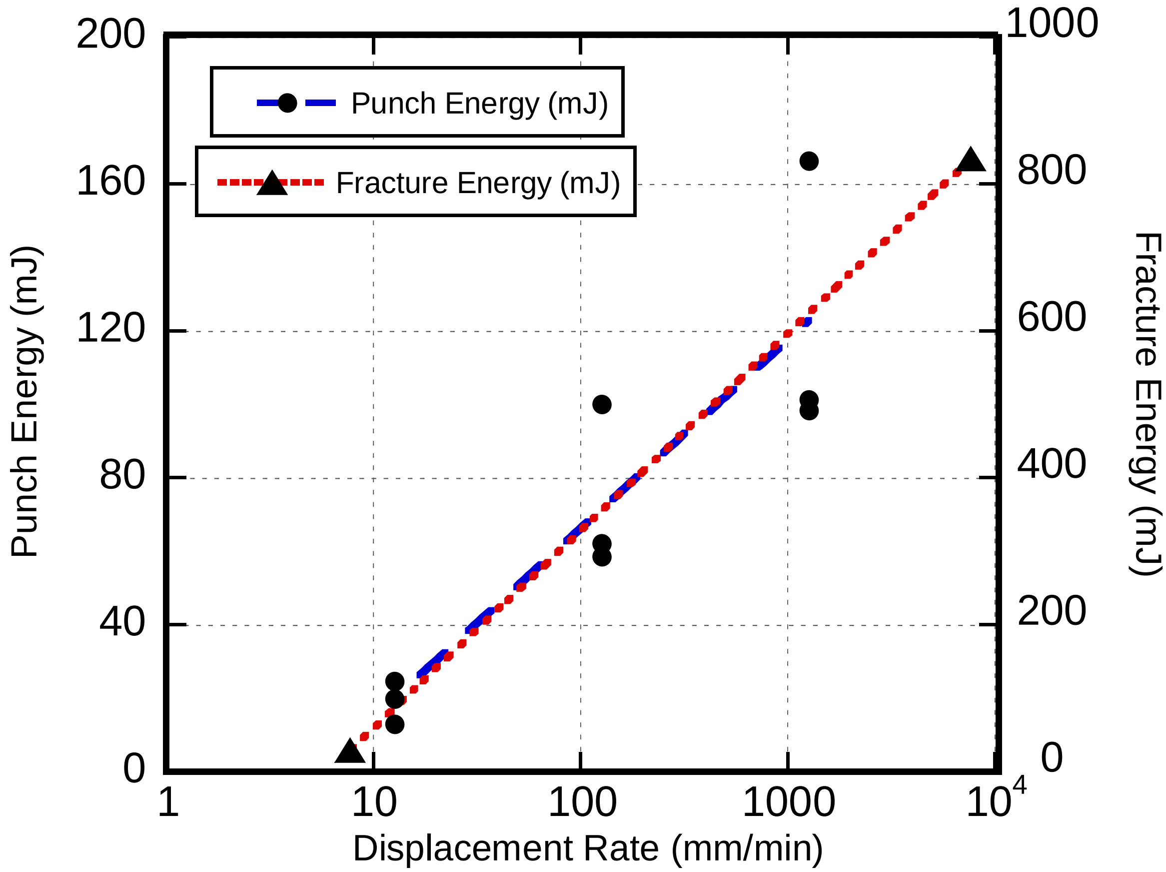


Figure 12. Relationship between punch energy and fracture energy for 20% ballistic gelatin.

From the differences in scaling of the punch energy and fracture energy used in the plots shown in figures 10–12, no gelatin had the same energy from both the punch test and previous fracture experiments. However, this result should be expected because of the difference in specimen and loading conditions. Also, the ratios of the two energies for the three gels were not equal. This provides no direct correlation of the punch energy data to previous failure energy data for these materials.

4. Summary, Conclusions, and Plans for Future Testing

A collection of different gelatin materials, all of different ingredients and concentrations, were tested to full failure using a hemispherical indenter. The displacements and loads required to puncture these specimens were recorded, and the test method was proven to give repeatable data for all gelatin types. Materials were characterized at extension rates of 12.7, 127, and 1270 mm/min. Similarities in response were found between synthetic gels and the ballistic gels, and data were compared to prior work on similar materials. This method benefits from simple material

preparation using low volumes of gelatin sheets and has minimal data reduction of only load and displacement. Vast differences in load response are apparent in each material formulation, and the test provides a useful method to distinguish the mechanical responses of these new materials. While this punch method did not directly correspond to past tensile fracture data, it is effective as a screening process for new gelatin materials to prove them suitable for further investigation as a tissue surrogate. It is somewhat outside the scope of this study to relate this current punch data to previous tests, considering that the irregularities and measurement error of this method have not yet been addressed.

The punch method previously described is sensitive to friction between the indenter and the gelatin surface, and while it was outside the scope of this study, relative size effects between the indenter and specimen diameters are likely. Further studies will investigate these issues and give a wider range of measurements from a similar biaxial loading condition. In order to eliminate the effects of surface friction, an investigation is planned where the indenter will be removed, and air pressure will be used to impart a distributed load on the specimen. We hope that the lack of friction will reduce the variation in failure mode seen in the PDMS-based gelatins, which seem more sensitive to friction than the other specimens. This method would also simplify optical strain measurement techniques for these transparent specimens because the indenter would no longer be in the background. By controlling the release and flow rate of incident air into the volume, a much wider range of loading rates could be attained than are achievable with the load frame used in this study.

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